Bringing Data Back From Mars: In-Situ Communications Role—The Rover to Orbiter to Earth Link

David Bell

Introduction

Over the coming decade, an international fleet of spacecraft will carry out the most intensive exploration to date of another world in our solar system. A wide range of orbiters, landers and rovers will conduct a linking together—detailed *in-situ* investigations, culminating in an eventual return of Martian surface, subsurface, and atmospheric samples to Earth for detailed laboratory evaluation. Program success depends on the implementation of an orbital infrastructure to support the telecommunications and navigation needs of this mission set. Definition of abbreviations and a glossary is provided at the end of the article.

Mars Program Overview

During 2000, a comprehensive replanning activity involving NASA and its international partners was carried out, establishing a new program of Mars exploration for the coming decade. The new plan incorporates program recommendations made after the loss of the Mars Climate Orbiter and Mars Polar Lander, and integrates a systematic science strategy laid out by the Mars Exploration Payload Advisory Group.

A timeline of the planned mission set is illustrated in Figure 1.

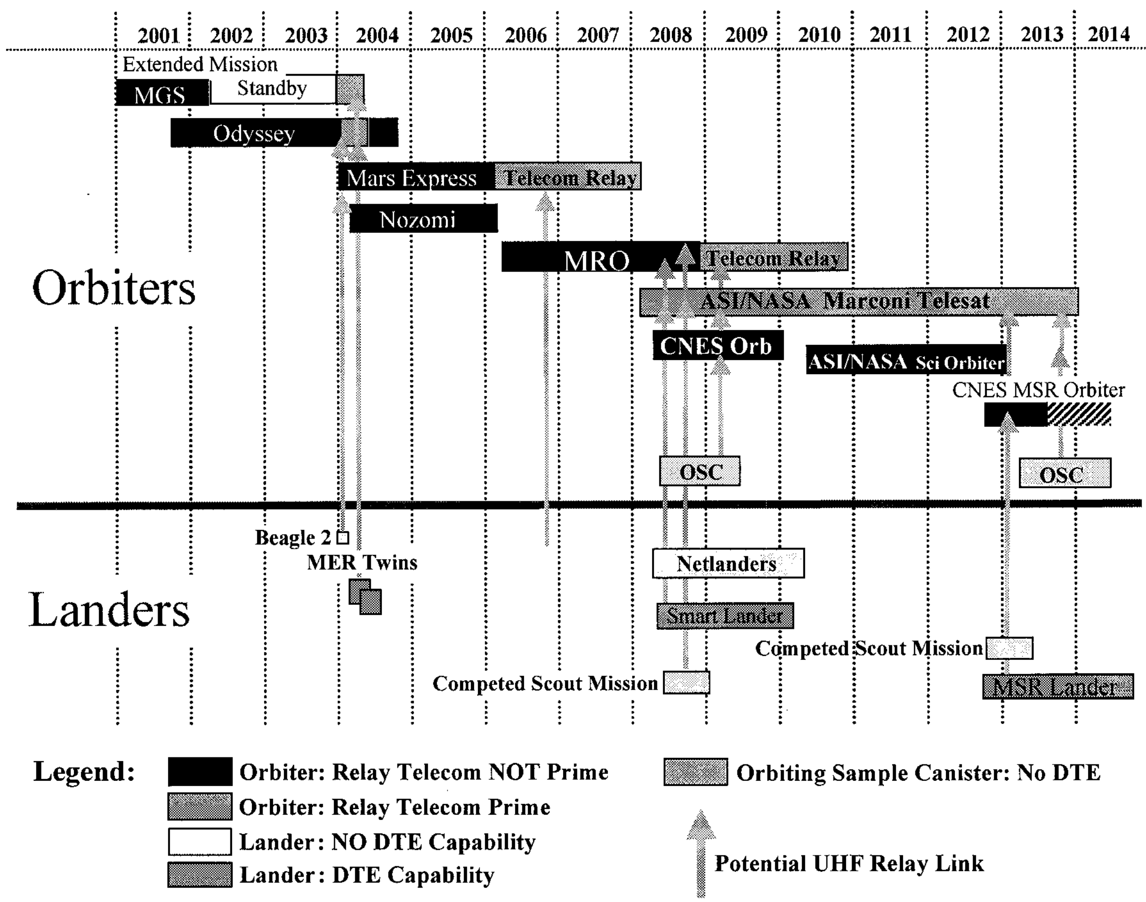


Figure 1: Mars exploration timeline

Key elements of the program include:

- *Sample Return:* A driving element of the program is a planned Mars Sample Return (MSR) mission launched in the 2011 Mars launch opportunity. This mission would utilize a NASA lander to select, obtain and launch them in an Orbiting Sample Canister (OSC). A Centre National d'Études Spatiales (CNES) orbiter would retrieve the OSC and return it to Earth
- *Technology precursor missions:* Key MSR technologies, include accurate pre-entry navigation, monitored entry/descent/landing (EDL), landing to an accuracy of 6 km or better, OSC orbit determination and rendezvous. The 2007 NASA "Smart Lander" and the 2007 CNES Orbiter missions will validate these and other key technologies prior to their use in the actual 2011 sample return.
- *Orbital reconnaissance:* To support site selection for sample return, in terms of both scientific and site safety considerations, the program includes a strong suite of remote sensing orbiters, including Mars Global Surveyor (NASA, '96), Mars Odyssey (NASA '01), Mars Express (ESA, '03), Nozomi (ISAS, '98), Mars Reconnaissance Orbiter (NASA '05), and CNES Orbiter ('07).
- *Competed scout-class missions:* In addition to the sample return mission and feed-forward technology precursor missions, the NASA program also incorporates competed scout-class missions, starting in the 2007 opportunity. These cost-capped, PI-managed missions are intended to broaden the science scope of the program and encourage innovative mission concepts that quickly respond to new scientific discoveries.
- *Telecommunication relay capabilities:* Recognizing the importance of telecommunications and radio-based navigation to the aggregate set of Mars missions, the program also provides proximity link relay telecommunications and navigation services based on an evolving orbital infrastructure. Near-term science orbiters such as Mars Global Surveyor (MGS), Odyssey, Mars Reconnaissance Orbiter (MRO), and CNES'07 will carry proximity link telecommunications payloads. In addition, the program includes the first dedicated Mars telecommunications spacecraft, the 2007 ASI/NASA Marconi telecommunications orbiter.

These ultra high frequency (UHF)-equipped orbiter elements form the centerpiece of in-situ telecom and navigation services for all other missions. The InterPlanetary Network and Information Systems Directorate (IPN-ISD) in-situ work area has focused on developing radio, antenna and coding technologies that will fly on orbiters and landed elements.

Relay Orbiters Enhance Operations

For the smaller mission elements, Beagle2 lander, Netlanders, Scouts and Orbiting Sample Canisters, the UHF relay telecom function is a mission enabler since they have no means to communicate directly to the Earth. For the larger landed elements, Mars Exploration Rover (MER), Smart Lander and MSR Lander/Rover, the UHF relay telecom can provide up to 10 times improvement in data return volume for the same or less expenditure of energy. For all of the missions, the orbiting infrastructure can provide navigation to assist in arrival and descent maneuvers as well as landed operations. Finally the orbiting relays provide a link to the night side of Mars that is hidden from the Earth's view.

It is easy to see why a short haul surface to orbiter relay link can out perform a direct to earth link. Communication difficulty increases as range squared. Mars to earth range can reach a maximum of 2.7 astronomical units (AU) or 400 million kilometers (km). Compare this to the in-situ link ranges of 1000 to 6000 km. The power loss to earth is over 100 decibels (dB) greater than on the in-situ link. This vast difference is difficult to make up even with the large Deep Space Network (DSN) antennas. Thus the shorter haul surface to orbiter relay link can out perform a direct to Earth link by reducing energy expended, shortening pass times and dramatically increasing data rates and data volumes. Figure 2 below shows several examples of this.

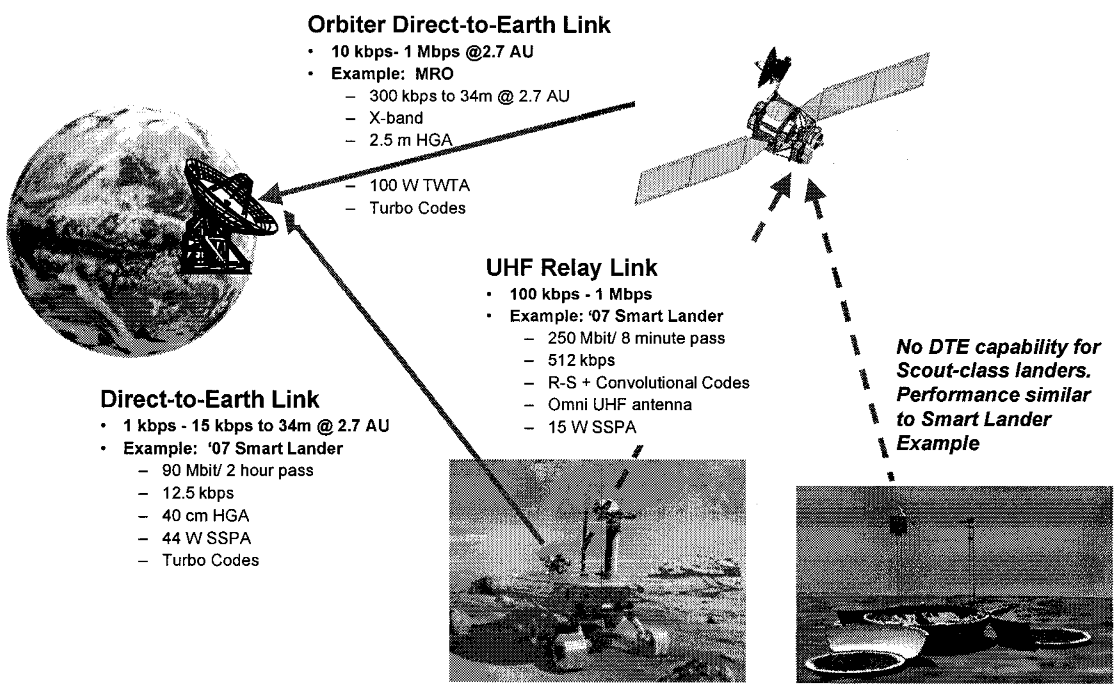
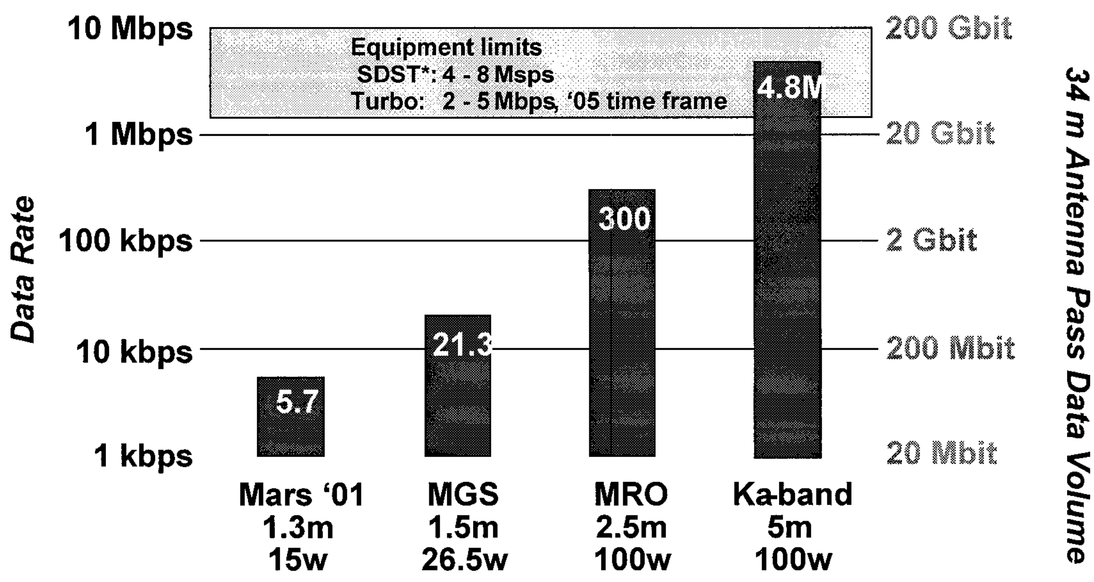


Figure 2: Relay links return more data than direct to Earth links

The enhanced performance of the relay link requires that the relay spacecraft have sufficient data storage and earth link capacity so that it does not become a performance bottleneck. Figure 3 depicts a brief history of telecom performance from Mars and shows that there is significant performance headroom we can access with reasonable technology advancements. The X-band equipment currently proposed for the MRO mission provides a factor of 14 increase in data return relative to its precursor imaging mission MGS. Even with this dramatic improvement, both MRO and MGS are data volume limited to imaging only 1% to 2% of the Martian surface at highest resolution. The MRO mission at 30 centimeters (cm) per pixel resolution generates 25 times more data than the 1.5 meters per pixel MGS camera when both spacecraft image the same surface area of the planet. Thus from a science perspective, we are still quite data rate limited from Mars. The expectation is for future orbiters to continue to move to higher Earth link capacity via a combination of Ka-band, larger deployable antennas and higher traveling wavetube amplifier (TWTA) power. On-board data storage capacity must also keep pace with the anticipated higher data volumes.

All of these advancements are beneficial to the evolution of relay telecom infrastructure. As Earth link data rates increase, we have more room to improve the performance of the surface to orbit link without choking the Earth link data pipe. Thus the potential for high volume data return on a relay link increases and the case for relay telecom, instead of direct to Earth data return, becomes stronger.



*Small Deep Space Transponder

Data Volume assumes 40 min of occultation per 2 hour orbit. Yields 5.83 hrs ofdownlinktime during a 10 hour DSN Pass

Figure 3: Past, Present and Future Mars Orbiter-to-Earth Data Capacities

These data rate calculations have been performed for maximum Mars-Earth range of 2.7 AU. As Mars-to-Earth range shortens down to as little as 0.5 AU, the *potential* link capacity rises by a factor of 25x. For example, during the shorter range portions of the MRO '05 mission, 1 AU or less, our potential long haul Earth link rate exceeds 2 Mbps and we move into an operating region were we are bandwidth and equipment limited rather than power limited. A move to Ka-band will solve the bandwidth concerns but pushes us further past the 2 to 8 megasymbols per second limits associated with the small deep space transponder and near term turbo decoders.

On the short haul Mars surface to orbit link, it is again the orbiter equipment that can really pump up the performance. Figure 4 shows the expected evolution in surface to orbit link performance. The surface element performance is assumed to be constant at 15 watts radio frequency (RF) and an omni-directional antenna. Increases in data throughput and data volume stem from the following design improvements.

1) Lower loss receivers.
   Newer UHF Electra radio technology that will fly on the Mars Reconnaissance Orbiter, Mars '05, and later missions will operate with 2 dB lower filtering and radio losses compared to the older UHF relay radio design that is flying on Mars '01.

2) Use of better channel codes on the relay link.
   Concatenating a (255,239) Reed Solomon code to the standard rate _ convolutional code improves the short haul link performance by over 2 dB. IPN-ISD technology development of on-board Turbo Decoders will add another 0.5 dB of performance improvement.

3) Higher gain spacecraft antennas and longer pass times
   The proposed joint Italian/NASA orbiter, Marconi, will be designed with relay telecom as the primary mission function. The 4450 km altitude, 130 degree inclination candidate orbit provides 3 to 5 passes per day to all Mars surface locations with an average per pass time of over 1 hour. This is a vast improvement when compared to the low altitude science orbiters that produce less than 3 passes per day with a typical duration of 7- 8 minutes for surface sites below 45 degree latitude. Another advantage of the higher altitude non-polar orbit is that it provides coverage across 6 – 12 hours of Mars local "time zones". Thus data can be returned at many different local times of day allowing for more operational flexibility. The lower altitude polar orbit used on science orbiters produce a narrow coverage swath that always views the same 2 hour local time zone.

   A drawback of the higher altitude orbit is the longer slant range to users. This is compensated for in the design of the Marconi telecom orbiter by the inclusion of a medium gain, 13–15 dB power (relative to isotropic source), steered antenna. Several helix, yagi and array UHF medium gain antennas are currently being studied under IPN-ISD funding. Compact storage, deployment and steering mechanisms are also part of these on-going investigations in the IPN-ISD in-situ telecom work area.

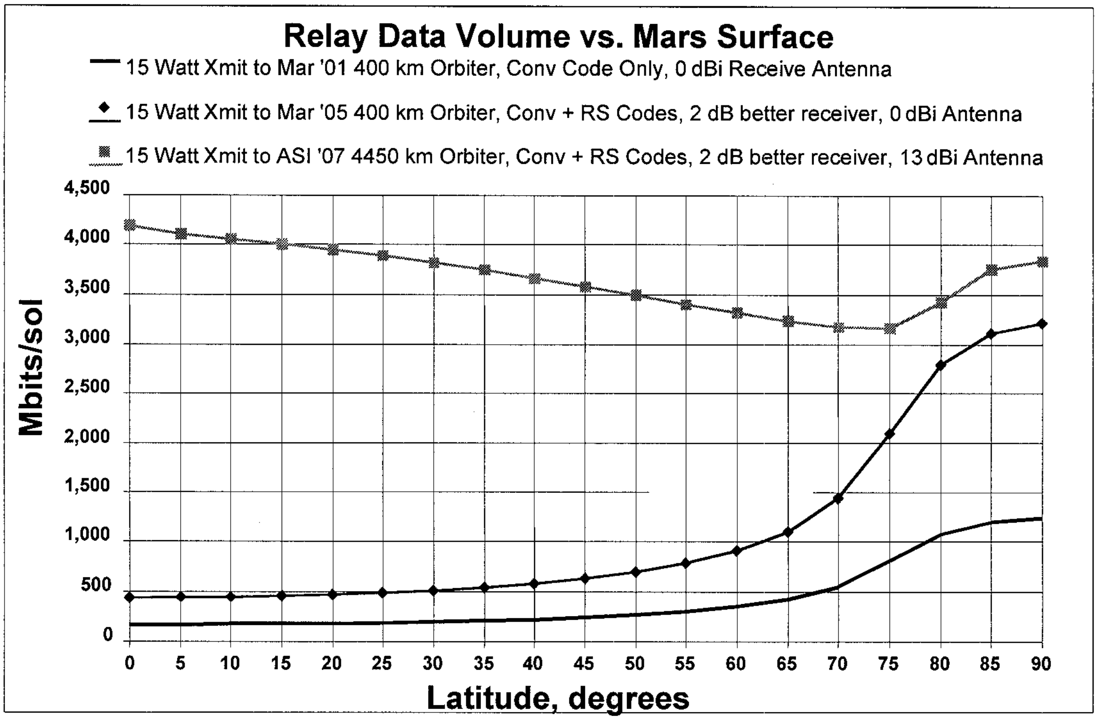


Figure 4: Evolutionary Improvements in Surface to Orbit UHF Relay Link Capacity

Again, the data volumes indicated above are potential numbers. If only the daytime passes are used, the data volumes are cut in half.

Are gigabits per sol from a single surface element required? Mission planners can certainly think up ways to use it. Initial planning on '07 Smart Lander and Sample Return missions include roving operations that will take one or more multi-spectral panoramic images every 100 meters (m) along the traverse route. This corresponds to 1–2 images returned per sol. Even with moderate image compression, single images could exceed 1 gigabit.

Electra Proximity Link Payload

For the past two years, IPN-ISD has funded the development of an in-situ radio, the Micro Communications and Avionics System. MCAS has been selected as the core of JPL's next-generation proximity link payload, called Electra. Electra will provide telecommunications relay and in-situ navigation services for future Mars missions. With a first flight on MRO, this payload could be flown on all subsequent Mars orbiters, provide *de facto* interoperability and would enable the gradual implementation of a Mars orbital communications/navigation infrastructure described earlier. Key high-level goals for Electra include:

- Flight reconfigurability to increase payload utility and accommodate new mission scenarios over long relay orbiter mission lifetimes
- Greater flexibility, including a wider range of supported data rates, swappable transmit/receive bands and simultaneous multi-channel operation.

- Full compliance with Consultative Committee for Space Data Systems (CCSDS) Proximity-1 Link Protocol [CCSDS, 2000] and CCSDS File Delivery Protocol [CCSDS, 1999]
- Addition of X-band (8.4 gigahertz [GHz]) receive capability, to support precision approach navigation, to support capture of EDL communications and to allow very high-rate reception of data from a lander equipped with a directional X-band DTE link.
- Improved navigation/timing performance
- Improved communications link performance through addition of Reed-Solomon coding, low-loss half-duplex operations mode, reduced receiver noise figure and increased power amplifier efficiency
- Modularity to allow scaling for low-mass lander/scout applications
- Portability to facilitate integration with a variety of orbiters and landed elements.
- Self-contained relay functionality (including relay data management) for improved testability

Current plans call for completion of an engineering model of Electra in early 2003.

Summary

The coming decade of Mars exploration will demand improved telecommunications capabilities to meet the needs of a wide range of mission elements. Increased deep space link performance will enable return of large science data sets from high-resolution remote sensing orbiters such as the 2005 MRO mission. Proximity relay communications will piggyback on these science orbiters to form a heterogenous constellation equipped with a standardized Electra communications/navigation payload, along with the first dedicated planetary relay satellite, the 2007 Marconi spacecraft. This orbital infrastructure must meet the diverse requirements of large, highly capable, second-generation landers/rovers as well as small, energy-constrained scout-class missions. Application of key IPN-ISD funded technologies such as lower loss receivers and increased gain UHF antennas on the orbiter and better channel coding on the surface to orbit link will allow significant increases in data return while minimizing the user's energy-per-bit requirements. The higher-altitude orbits being considered for Marconi spacecraft will increase temporal coverage for all Mars latitudes from minutes per day to hours per, day providing relay telecom users with much more operational flexibility and the potential of returning gigabits per day through the relay link.

Abbreviations

The following abbreviations are used if not otherwise spelled out in this article.

Abbreviation	Meaning
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
AU	astronomical units
CNES	Centre National d'Études Spatiales
CCSDS	Consultative Committee for Space Data Systems
DTE	Direct to Earth
dBi	dB power relative to isotropic source
EDL	Entry, Descent, and Landing
ESA	European Space Agency

Gbit	gigabit
HGA	high-gain antenna
IPN-ISD	InterPlanetary Network and Information Systems Directorate
ISAS	Institute of Space and Astronautical Science
kbps	kilobits per second
MGS	Mars Global Surveyor
MRO	Mars Reconnaissance Orbiter
MER	Mars exploration rover
Mbps	megabits per second
MCAS	Micro-Communications and Avionics System
M/pixel	Meters per pixel
R-S	Reed-Solomon
SDST	Small Deep Space Transponder
SSPA	solid-state power amplifier
TWTA	traveling wavetube amplifier
UHF	ultra high frequency
yagi	shortwave antenna

Glossary

The following glossary may help understand terms used in this article.

Term	Meaning
Electra Proximity Link Payload	Electra is the name give to the next generation of UHF radio that will perform in-situ communications between landers and orbiters. Just like science instruments, the Electra radio rides as a payload on a host spacecraft, lander or orbiter. Proximity link is a standard term used by the Consultative Committee for Space Data Systems (CCSDS), an international radio and communications standards group. There is actually a "CCSDS Proximity-1" protocol standard that will be implemented on the Electra radio.
in situ	Latin for "in the natural" or "original situation" or "place".
In-Situ communications	Communications local to Mars. Mars landers and orbiters need to communicate with each other. The surface to orbiter link is used as the first hop-in relay communications to earth. A rover-to-lander link can be used. An orbiter to orbiter link might be used to collect radio metric information. These are examples of in-situ communications, that is, communication between elements in the Mars local environment.
In-Situ radio	A radio designed specifically to operate with standards, frequencies and protocols specified for in-situ communications.
In-Situ telecom	Same as In-Situ communications above
orbiter relay link	Meaning surface-to-orbiter relay link—a relay link because the orbiter serves as the relay point on the data pathway to Earth and the lander to orbiter portion is the first leg of the relay. We could also have a rover-to-lander relay link, the idea being that the lander acts as the relay point and the rover-to-lander link is the first leg of this relay link.
pass time	Interval of time that a landed element can see an orbiting spacecraft in the sky. During this time, the element can send data up to the orbiter and the event is called a "pass," just like the DSN stations have 6-12 hour passes of objects they view in the sky. Pass times are usually referenced to some minimum elevation angle also, that is, the spacecraft must appear some minimum angle above the horizon before the pass starts and the pass ends when the spacecraft falls below this minimum elevation angle as viewed by the surface elements.
Proximity link	Another phrase for in-situ link or in-situ communications. A short-range communications or navigation radio link

Proximity relay communications	Same as described above, just different phrasing
Relay link	Same as described above, just different phrasing
Relay telecom	Same as described above, just different phrasing
R-S + Convolutional codes	To increase the performance of error correcting codes, they are often combined end-to-end. First the data is Reed-Solomon (Irving S. Reed and Gustave Solomon) encoded, then it is convolutionally encoded. The short hand for such a concatenated coding scheme that involves Reed-Solomon and Convolutional codes is "R-S + Convolutional."
short haul surface to orbiter	With an intended pause between "haul" and "surface", "short haul" is describes the "surface to orbiter relay link." Short haul is in contrast to the long haul link to earth, trucking terminology adopted by the communications community.